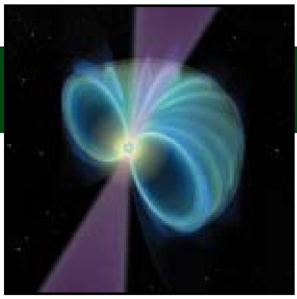

# Spacecraft Navigation Using X-ray Pulsars

P.S. Ray, K.S. Wood, and B.F. Phlips
*E.O. Hulburt Center for Space Research*

Pulsars are the collapsed remnants of massive stars that have become neutron stars, where a mass exceeding that of the Sun is packed into an area about the size of the DC Beltway. Many of these neutron stars spin rapidly (hundreds of times per second) on their axis and emit pulsations at the spin frequency in much the same manner as a lighthouse. These natural "lighthouses" can also be used for navigation, that is, determining the position, time, and attitude of a spacecraft. Because of their enormous mass and relatively simple structure, pulsars are exceptionally stable rotators whose timing stability rivals that of conventional atomic clocks. A navigation system based on celestial sources will be independent of GPS and available in any Earth orbit as well as in interplanetary and interstellar space. NRL has undertaken a program to characterize and model X-ray pulsars and build X-ray detectors for a planned flight demonstration of this technology.

## INTRODUCTION

Since prehistoric times, celestial sources such as the stars, Sun, and Moon have been used as navigation aids. Observations of the sky with precision instruments can allow explorers to determine their local time and latitude and longitude with high accuracy. Modern navigators still use some of these techniques. But they have also come to rely on man-made systems such as the Global Positioning System (GPS). These systems can provide a user with position, velocity, and time with exquisite accuracy—regardless of whether it is night or day, or what the weather is.

Over the last decade, GPS has revolutionized the navigation of everything from rental cars, to commercial aircraft, to precision-guided munitions. Nevertheless, there are some situations, particularly involving spacecraft navigation, where GPS does not provide a satisfactory solution. The most obvious situation is for spacecraft that must operate outside the orbit of the GPS constellation, which is at an altitude of 20,000 km. In addition, a spacecraft with a mission of national importance might want to have an additional source of navigation information besides GPS to increase its robustness to threats.

When considering alternative navigation methods, it is instructive to review how GPS works. GPS consists of a constellation of about 24 satellites, each carrying several precise atomic clocks that periodically broadcast a radio signal containing the precise time according to their clock (and ancillary information including the location of each GPS satellite). A GPS receiver receives the radio signal from several satellites and computes the range (technically *pseudorange*) to each satellite based on the time difference between transmission and reception of the signal and the propagation speed of the radio signal. Using information from at least four satellites, the receiver can thus solve for its own position and the precise local time.

The celestial bodies we are familiar with, based on our experience observing the sky with our eyes, are not particularly promising in this regard because they do not broadcast a precise timing signal that can be used for navigation (except for a few isolated examples such as eclipses of the moons of Jupiter). However, the 1967 discovery of *pulsars* changed that situation dramatically by demonstrating that at least some celestial sources *do* broadcast highly regular timing signals. This led to the proposal to use pulsars as the basis for a spacecraft navigation system based on observations of celestial sources, using them as a kind of "natural GPS." It presents a trade of flexibility, high performance, and man-made control on the GPS side vs zero maintenance and universal availability on the side of the natural sources. The achievable level of performance in the latter case is something that can be settled by practical experiments. Hence, it becomes an interesting objective for a research program.

In this article, we describe the properties of pulsars that make them attractive as potential natural navigation beacons and why a practical implementation looks most feasible in the X-ray band. We then describe the history of the X-ray navigation program at NRL up through our current Defense Advanced Research Projects Agency (DARPA) program. Finally, we describe the custom X-ray detector modules we are developing for this program and some of the algorithmic challenges that must be overcome to implement a real system.

## PULSARS: NATURE'S BEST CLOCKS

A pulsar is a rapidly rotating neutron star that is observable as a pulsed source of electromagnetic radiation. Neutron stars are formed in the core collapse of a massive star and are the most dense form of matter in the Universe, with central densities that exceed the density of an atomic nucleus! As the core collapses, conservation of angular momentum causes the star to "spin-up" to a rotation period of order 10 ms, and the conservation of magnetic flux drives the magnetic field strength at the stellar surface up to $10^{12}$ gauss or higher, with magnetic moments up to $10^{32}$ gauss-cm$^3$.

The resulting object is simultaneously a massive freely spinning top and a powerful particle accelerator because the rotating magnetic field generates enormous electric fields that accelerate charged particles. These accelerated particles generate electromagnetic waves across the spectrum, from radio waves to gamma-rays, that tend to be beamed along the magnetic axis. If, as it appears true in most cases (including the Earth), the magnetic axis is misaligned with the rotational axis of the star, a distant observer sees a "pulse" of radiation each time the beam crosses the line of sight, much like a lighthouse (see Fig. 1). The energy that powers these cosmic lighthouses is simply the stored rotational energy of the neutron star. As the energy is slowly radiated away, the star "spins down" to longer and longer rotation periods, and thus these sources are referred to as *rotation-powered* pulsars. They shine in this manner for a period of about ten million years, after which time they have slowed down to a period of order 10 seconds and can no longer generate the strong fields necessary to accelerate the particles that produce the powerful radiation beams. These pulsars then turn off and inhabit the "pulsar graveyard."

During their lives, these pulsars make very good clocks; their periods change by only 100 ns or so each year. Nevertheless, even this paltry rate of slowing causes the star to get out of equilibrium as the rotation of the crust gets out of sync with the superfluid interior. This causes timing irregularities, both gradual (the long-term stochastic wandering of the pulse phase, referred to as "timing noise") and sudden (nearly instantaneous "glitches" in the pulse period that happen when crustal strains build up to the breaking point). These unpredictable irregularities limit the usefulness of these "normal" pulsars as navigation beacons. However, another class of pulsars is much more stable and promising, the *millisecond pulsars*.

The millisecond pulsars are formed when a pulsar has a binary companion that is a normal star. At some point, stellar evolution or orbital dynamics brings the two stars into contact, and a large amount of matter is transferred from the normal star onto the pulsar in a process known as accretion. During the mass transfer process, these systems become tremendously bright X-ray sources as the infalling matter is heated to temperatures of millions of degrees. The mass transfer also causes two other effects: it transfers angular momentum to the pulsar, spinning it up to periods near 1 ms, and it causes the magnetic field of the pulsar to decay by about a factor of 10,000. When the accretion process stops, the pulsar is reborn as a millisecond pulsar (also called a "recycled pulsar"). The greatly reduced magnetic fields of these pulsars causes them to spin down much more slowly (their period changes by less than 1 picosecond per year!) and live for far longer (tens of billions of years) than the normal pulsars. As a result, the millisecond pulsars are exceptionally stable clocks, whose stability rivals modern atomic clocks (see Fig. 2)!

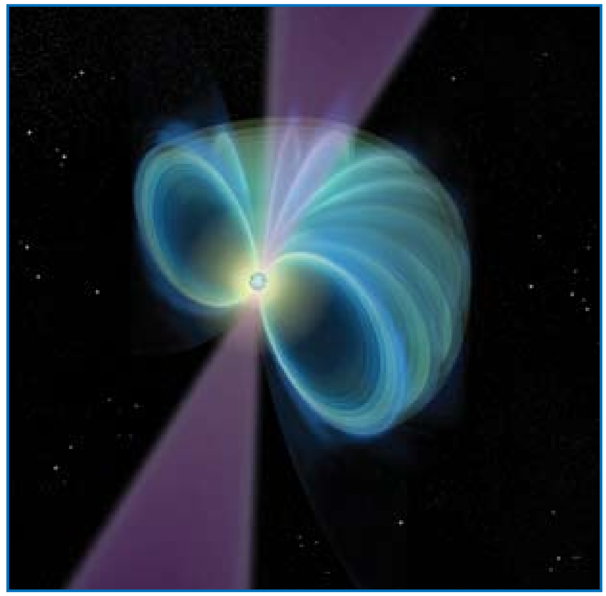

**FIGURE 1**
Artist's conception of a rotation-powered pulsar.

### Why Observe Pulsars in the X-ray Band?

Nearly all pulsars (more than 1500 are now known) are discovered and studied in the radio band, using ground-based telescopes. However, most radio pulsars are very faint and can only be studied with the world's largest radio telescopes, such as the 305-m Arecibo telescope in Puerto Rico, or the 100-m Green Bank Telescope in West Virginia. The requirement for huge antennas makes a navigation system based on radio observation of pulsars impractical for most applications. In addition, propagation of radio signals through the interstellar medium results in phase lags of variable and unpredictable duration, so that they set the limitation on accuracy.

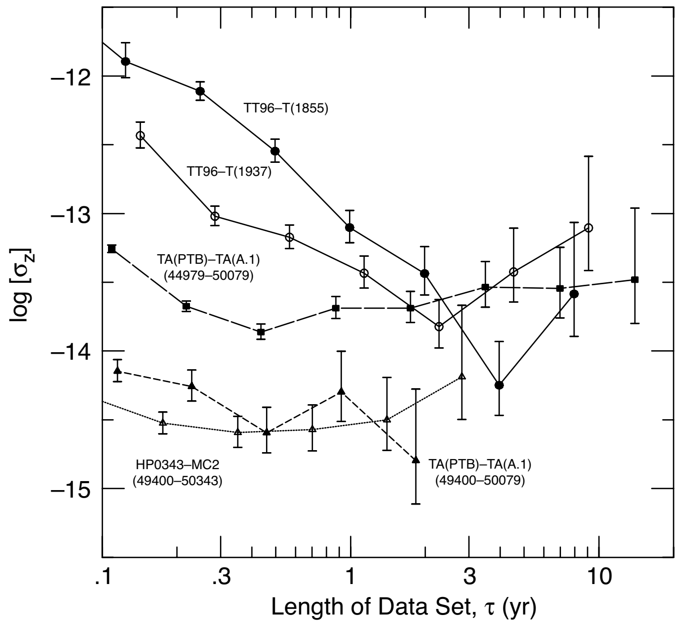


**FIGURE 2**
A comparison of the stability of two millisecond pulsars with some atomic time scales. $\sigma_z$ represents the fractional stability of one clock compared to another (it is analogous to the Allan variance used in the clock community). T(1937) and T(1855) are the timescales based on the pulsars PSR B1937+21 and PSR B1855+09, respectively. TT96 is a terrestrial atomic timescale. TA(A.1) and TA(PTB) are free running atomic timescales from the U.S. Naval Observatory and Germany. Notice that at long timescales, the pulsar timing stability approaches that of modern atomic time standards. (Reproduced from Matsakis, Taylor, and Eubanks 1997, *Astronomy & Astrophysics* **326**, 924.)

However, a modest number of pulsars are known to emit pulsed X-rays as well, that can be detected by an X-ray instrument that is less than one square meter (1/70,000th the size of Arecibo!). The X-ray signal, at effectively infinite frequency, is not affected by the interstellar medium like the radio signal, and thus several limitations to the precision of the timing measurements are removed. The primary drawback of using X-ray detectors is that X-rays do not go through the Earth's atmosphere, so the method is limited to space applications. Other drawbacks include the small number of known X-ray millisecond pulsars and their relative faintness, which leads to a requirement for a large X-ray detector to make precision measurements (though still tiny compared to the radio dishes that would be required).

## HISTORY OF X-RAY NAVIGATION AT NRL

In the 1980s, the NRL X-ray astronomy group (now Code 7655) was specializing in studies of timing effects in celestial X-ray sources such as pulsars or black holes. In these objects, certain timing signatures were periodic, as in the rotation periods of pulsars or the orbits of binary systems. Others were quasi-periodic or aperiodic; some of these effects are produced by fluid modes involving movement of hot gas in the source systems. Many of the timing studies were conducted with simple instruments of a kind used at NRL since the early work of Herbert Friedman and collaborators, in which a sensor sensitive to X-rays is combined with a collimator that accepts incoming photons from only a small region of the sky, perhaps a square degree. There are no X-ray mirrors in such systems yet they can readily isolate the brightest sources in the sky, say ~1000 of them. It was recognized that the combination of simple detector systems with the outstanding feature of the X-ray sky—an abundance of variable point sources—implied a potential for X-ray navigation.

### USA Experiment on *ARGOS* (1999-2000)

During the 1980s, this abstract idea took on a concrete form with the proposal to fly a demonstration experiment called the Unconventional Stellar Aspect (USA) Experiment. When finally realized with launch in February 1999 on the Air Force *Advanced Research and Global Observation Satellite* (*ARGOS*), USA had become an X-ray astronomy experiment with four distinct objectives: astronomy, autonomous satellite navigation, atmospheric diagnostics, and testing techniques for computing in space.[1] It was built by NRL in collaboration with Stanford University, using funding from the Navy, the Department of Energy, and the Ballistic Missile Defense Organization. From the first proposal (1988) to launch took 11 years. Some of that time went into selling the idea, and some went into evolving the multipurpose system concept that was eventually flown.

USA used an X-ray photon sensor as its central element; the sensor was mounted in a 2-axis gimbal for offset pointing from *ARGOS*.[2] The sensor was designed to look at both stars and the Earth, supporting both astrophysics-related observations and experiments in X-ray navigation. For either goal, it was necessary to do offset pointing, which involved onboard computation. There was also a computing experiment involving testing MIPS-3000 class processors in space. The motivating idea was that this could take data from the X-ray sensor and derive navigational quantities onboard, but it also served as a testbed for space-based fault-tolerant computing techniques. The computing testbed operated independently of the astronomy effort so that comparative (and rather surprising) flight experience was gained with both commercial off-the-shelf and specially radiation-hardened processors. Figure 3 shows the USA instrument, mounted in its 2-axis gimbal and pylon. The overall weight of the USA Experiment was approximately 200 kg, including sensors, pylons, and gimbals.

**X-ray Navigation and Aeronomy with USA**

The instrument was successfully used for experiments in autonomous attitude determination, position determination, and time-keeping using X-ray sources, all of which fulfilled its navigational objective. It was also used to study the density of the atmosphere at altitudes of roughly 50–80 km using a technique similar to X-ray tomography. The central aim of the navigational part of the program was to explore how well observations of X-ray sources could be used to determine the attitude, position, and local time for a satellite in orbit.

*Attitude*

As it happened, USA had to be used to diagnose and correct unexpected errors in the performance of the spacecraft attitude control system that initially caused it to miss targets. This was the first use of an X-ray sensor to provide diagnostic attitude information for the control of a satellite in orbit. Since USA was not an imaging system, attitude determination was done using transits of sources through the response of the collimator. When an X-ray source drifts slowly through the field of view, it traces out the angular response function, which is roughly triangular. Early in the *ARGOS* mission, the USA team began doing maneuvers in which the instrument was repeatedly scanned over known sources to measure the accuracy of the onboard attitude determination. To isolate and quantify satellite pointing errors so as to correct the problem, it was necessary to combine observations of several sources, as was done successfully during observations in August 1999. Once the instrument was used to diagnose problems in the attitude reference provided by the spacecraft itself, it became possible to track stars with high accuracy.

*Timekeeping*

Timekeeping experiments depend on using the best astronomical clocks, isolated pulsars. The pulsar in the Crab Nebula is the brightest in the X-ray sky, although it is not the most stable clock. Nevertheless, its strong signal makes it the source of choice for initial timekeeping studies. Figure 4 shows the pulse profile of the Crab pulsar; it had a period of 33.4033474094 ms at the time of the observation. The photons had their arrival times recorded using an onboard GPS receiver, and the pulse arrival times were compared to those predicted from ground-based radio measurements. The two were found to agree to about 100 μs, approximately the accuracy of the radio ephemeris. The ultimate limits of X-ray pulsar timing methods will be set by more stable pulsars such as PSR B1937+21, whose pulse period is 1.555780646881979 ms.

*Position*

USA demonstrated a technique for position determination using stellar occultations by the Earth's limb as measured in X-rays, which is distinct from the pulsar-based methods. This works for satellites in low Earth orbit (LEO). The exact time when the source

**FIGURE 3**
The USA Experiment mounted on the *ARGOS* spacecraft.

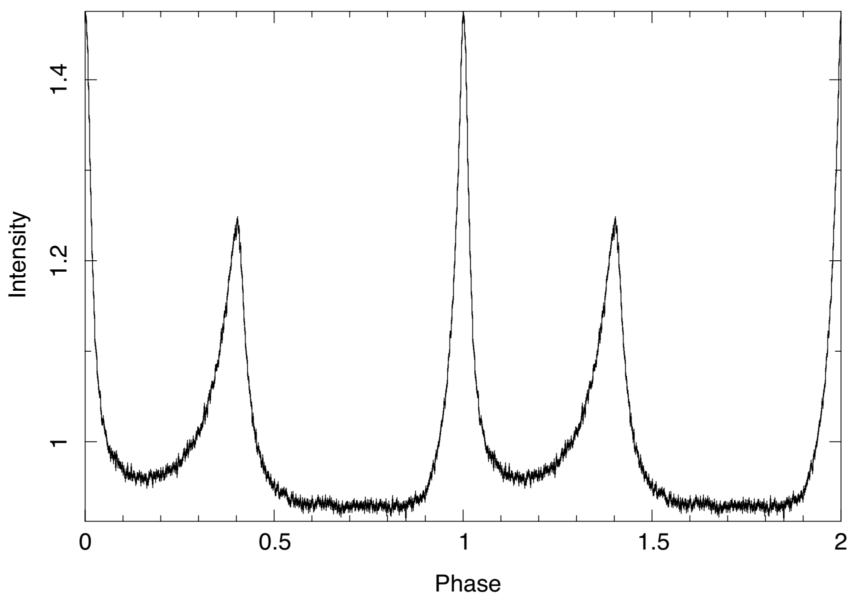


**FIGURE 4**
Average pulse profile of the Crab pulsar, recorded with the USA Experiment.

is eclipsed (say, when intensity is reduced to 50%), combined with an atmospheric model, will give the satellite position. This is like a classical horizon sensor except that here the sensor uses X-rays, not visible light. X-rays are absorbed at high altitude, not near sea level, and are not refracted or affected by dust or clouds. It is not possible to use the occultation method to determine positions accurately unless the density profile of the upper atmosphere is modeled properly, but work on this is also being done with USA data to fully characterize the technique.

### The DARPA XNAV Program

Since the initial navigation concept demonstrations with the USA Experiment, interest in the possibility of X-ray source-based navigation has greatly increased from within both DoD and NASA. In particular, DARPA has initiated a program it calls XNAV. DARPA is funding two teams, one led by our group at NRL, to perform an 18-month Phase I study of the XNAV concept. Our DARPA-funded work at NRL consists of two task areas:

- a detailed study of the most promising pulsar sources for this application, and
- development of laboratory prototype X-ray detectors well matched to the XNAV tasks.

Our collaborators on this effort include Massachusetts Institute of Technology and Brookhaven National Laboratory. At the completion of Phase I, DARPA will decide whether to fund Phase II, which involves the development and launch of a prototype XNAV instrument suite for an on-orbit flight test of the technologies and algorithms involved.

## THICK SILICON PIXEL DETECTORS

To make precise timing measurements of these X-ray pulsars, a detector system is required that is low-power, low background, and capable of sub-microsecond timing accuracy on each X-ray photon received. The detectors need to be large because the pulsars of interest are all rather faint. It must also be light weight and highly reliable in the harsh, high-radiation environment of space, and not require heavy and expensive cryogenic cooling. Previous X-ray detection satellite missions have used gas-based detector technology (e.g., HEAO A-1, RXTE, USA). These detectors are prone to leaks in the entrance window (from micrometeorites), as happened with the USA experiment. The detectors, although made of low density gas, can be rather heavy because of the massive frames required to contain the gas. An alternative technology is therefore of interest. As part of our DARPA program, we are developing prototype silicon pixel detectors that achieve all of these capabilities.

Silicon X-ray detectors are silicon PIN (p-type, intrinsic, n-type) diodes that are reverse-biased with high voltage until the entire silicon volume is depleted of free charge carriers. Under these conditions, an incoming X ray that interacts in the silicon will create a high energy electron, whose ionization track will create a large number of secondary electrons and holes. The electrons and holes drift under the electric field to the surface contacts, where they can be collected into preamplifiers and generate signals whose amplitude is proportional to the energy deposited by the X ray. The time response of the detectors is very fast and is dominated by the drift time of the electrons across the thickness of the detector. The drift time is ~20 ns/mm in silicon at room temperature.

The thickness of the detectors determines the efficiency of stopping higher energy X rays. Since X rays can be quite penetrating, thick wafers are required. For the XNAV program, as many X rays as possible should be detected, to maximize the accuracy for navigation. Therefore, the detector energy range should be maximized, requiring the detectors to be made as thick as possible to stop high energy X rays. The thickest silicon detectors currently manufactured are 2 mm thick, and we chose this thickness for our prototype detectors. Realistic detector configurations will require frontal areas much larger than the largest single pieces of silicon currently available. The instrument must therefore be modular and use large silicon devices to minimize the number of modules required for a particular instrument concept. The largest detector-grade silicon wafers available have a diameter of 150 mm. We are developing detectors that are 95 × 95 mm in area, the largest square device that can be obtained from the 150-mm wafers.

If the entire area of a wafer were read out as a single pixel, the capacitance of that pixel would be very large. The intrinsic noise performance of any preamplifier reading out that pixel would be very poor because the noise in a preamplifier is linearly dependant on the capacitance on the input of the preamplifier. The silicon wafers are therefore segmented into many small pixels, even though the pixels are not used for imaging. As the number of pixels grows, the capacitance of each pixel shrinks and the noise performance improves. But as the number of pixels increases, the power available per pixel decreases, which worsens the preamplifier noise performance. Simulations have shown that the optimal number of pixels per side of a wafer is 35-40, with a power budget of 0.7 W per wafer for the analog electronics. With this power budget, a noise performance for the electronics of ~50 electrons equivalent noise charge (~180 eV energy resolution) is expected with 1-μs filtering. We selected 36 pixels per side, for a total of 36 × 36 pixels per wafer. Figure 5 shows a prototype silicon X-ray detector wafer.

Custom electronics are required to read out all the pixels on a silicon wafer. To interface to all the pixels, the wafer needs to be bump-bonded to the readout electronic card. On this card, pre-amplifiers and amplifiers are connected to each pixel. The required circuit density and power budget demand the development of a custom application specific integrated circuit (ASIC). Such a program was started in collaboration with Brookhaven National Laboratory. Each wafer is to be read out by a 6 × 6 array of ASICs, each of which is connected to a 6 × 6 array of pixels. Each ASIC therefore contains 36 parallel channels of preamplifier, shaping amplifier, discriminator, and peak detection. The preamplifier amplifies the very small signals of a few thousand electrons by a factor of ~1000 and is followed by a shaping amplifier that filters out low- and high-frequency noise. The discriminator provides an adjustable threshold for signal detection and also provides a timing signal to mark the arrival time of a photon. The peak detection holds the peak amplitude of the transient pulse for later multiplexing and digitization in an analog-to-digital converter (ADC). The ASICs, ADCs, and ancillary electronics are controlled by a field programmable gate array (FPGA) that is in turn controlled from a computer. The amplitude of the pulse and time of arrival of the photon are recorded and stored in the computer for analysis.

**FIGURE 5**
Prototype 2-mm thick large-area silicon X-ray detector.

### ALGORITHMS FOR POSITION AND TIME DETERMINATION FROM PULSAR OBSERVATIONS

The basic measurement that yields position and time information is the arrival time of a pulsar pulse at the detector. This arrival time is then compared to the expected arrival time based on a timing model of the pulsar that has been developed from years of observations at ground-based radio telescopes. The difference between the observed and predicted arrival time can be translated directly into a correction in the position of the detector in the direction of the pulsar being observed (Fig. 6). Observations of multiple pulsars can thus be combined to provide full three-dimensional position information. Similarly, if the position of the detector is known, the time difference can be used to correct the time of the onboard clock. In practice, the spacecraft must keep a continuously updated model of its position and velocity state vector. This model is propagated forward in time using a high-precision orbit propagator; corrections to the model based on the pulsar observations are incorporated using a Kalman filter[3] (Fig. 7).

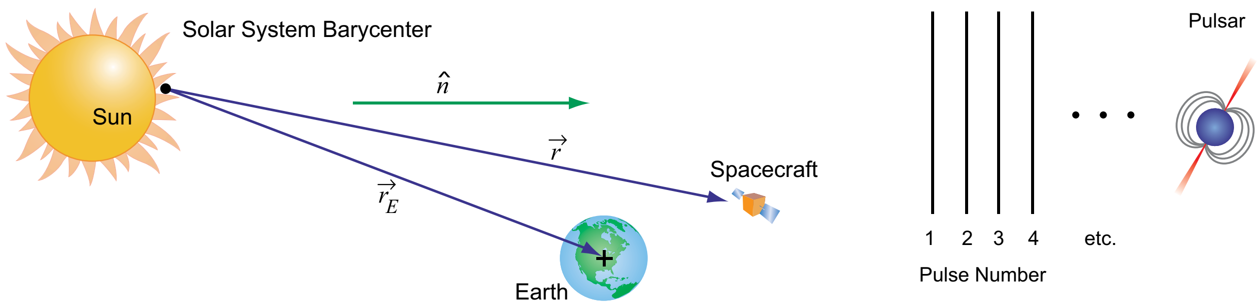


**FIGURE 6**
Observation geometry for X-ray pulsar-based navigation.

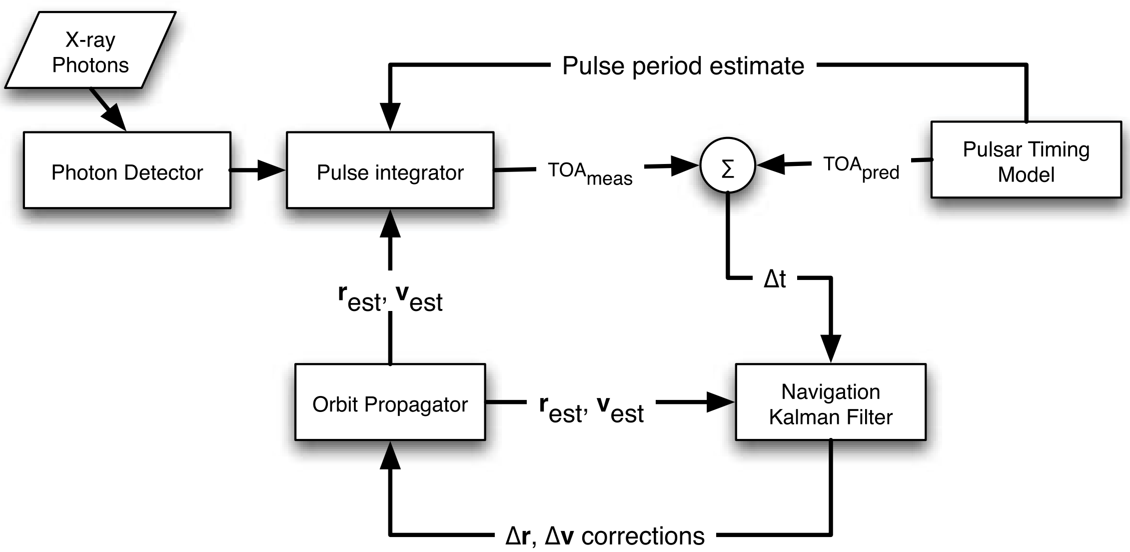


**FIGURE 7**
Flow chart of the basic algorithm for incorporating pulsar timing information into a navigation Kalman filter.

The details of the algorithm design depend very strongly on the requirements of a particular operational concept. Applications that we have considered include: time synchronization of multiple satellite clocks using a pulsar-based time scale; position and time determination for DoD satellites in highly elliptical or geosynchronous orbit or cislunar space; and precision navigation of spacecraft on interplanetary, or even interstellar, missions.

## CONCLUSIONS

The High Energy Space Environments Branch at NRL continues to explore the possibility of using X-ray pulsars as natural navigation beacons to provide time, position, and attitude information for spacecraft under a variety of operational concepts. Our plans for the future include detailed development of the algorithms required for the onboard processing of the raw pulse times-of-arrival and an advanced flight test of the detector system. We are also pursuing additional applications for the X-ray detectors such as a potential future large-area X-ray timing mission with ten times the collecting area of NASA's *Rossi X-ray Timing Explorer*. This could probe the behavior of matter in the strong gravity around neutron stars and black holes in a way never before possible.


## ACKNOWLEDGMENTS

We gratefully acknowledge the contributions of our many collaborators at NRL, Stanford University, Massachusetts Institute of Technology, Brookhaven National Laboratory, the University of Maryland, and elsewhere, whose efforts made the USA Experiment and our X-ray navigation program so successful.

[Sponsored by DARPA]



**References**

[1] K.S. Wood, "Navigation Studies Utilizing the NRL-801 Experiment and the ARGOS Satellite" in *Small Satellite Technology and Applications III*, ed. B. J. Horais, *SPIE Proc.* **1940**, 105 (1993).

[2] P.S. Ray, K.S. Wood, G. Fritz, et al. "The USA X-ray Timing Experiment" in *Proceedings of X-ray Astronomy 1999 — Stellar Endpoints, AGN and the Diffuse Background*, Bologna, Italy, *AIP Conf. Proc.* **599**, 336 (2001).

[3] S.I. Sheikh, D.J. Pines, P.S. Ray, K.S. Wood, M.N. Lovellette, and M.T. Wolff, "Spacecraft Navigation Using X-ray Pulsars," *J. Guid., Cont. Dyn.* **29**, 49 (2005).